USE OF SURFACE MEASURING PROBES

Cross Reference To Related Applications

5   This is a continuation-in-part of US Patent Application
No. 10/191,460 filed on 10 July 2002, which is a
continuation of US Patent Application No. 09/701,735
filed on 4 December 2000, which is the National Stage
of PCT/GB00/01315 filed on 7 April 2000, which are
10   incorporated herein by reference.

Background of the Invention

The present invention relates to the measurement of
15   workpieces using a surface measuring probe.

Measurement probes are known which have a stylus which
is deflectable when acted upon by a force as a result
of contact between the stylus and the surface of an
20   object. One or more transducers within the probe
measure the deflection of the stylus (usually in three
orthogonal coordinate directions) in order to obtain
information about the position of the surface. In use,
such a probe is mounted in a machine such as a
25   coordinate measuring machine (CMM), machine tool,
measuring robot or other coordinate positioning
apparatus. The machine moves the probe around the
object to be measured. Measuring devices in the
machine give outputs relating to the position of the
30   probe, which when combined with the outputs from the
probe itself enable information to be obtained about
the size, shape, position, surface contours, etc of the
object.

Such a measuring probe may be referred to as an
"analogue probe", distinguishing the measurement
outputs of its transducers from probes which merely
produce a trigger signal upon contact with an object.

5   The term "scanning probe" may also be used, since such
probes are often used for scanning the surface contour
of an object. Even though the term "analogue probe"
may be used, the outputs of the transducers may in fact
be analogue or digital.

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In known systems, measurement errors are caused by
deflections of the probe and machine structure. For
example, when the stylus is deflected, it is de-biased
towards a zero position e.g. by springs, and these

15   forces cause bending of the probe stylus and of
structural components of the machine. Whilst small,
such deflections can nevertheless affect the accuracy
of measurement, in view of the extremely high
accuracies nowadays demanded.

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Our earlier International Patent Application WO92/20996
describes a method of measurement in which such a probe
is moved into contact with the surface of an object to
be measured, and the movement is continued for a

25   further limited distance after initial contact has been
made. During this movement, the outputs of the
measuring devices of the machine and the transducers of
the probe are simultaneously recorded at a plurality of
instants. These recorded outputs are then used to

30   compute, by extrapolation, the values of the outputs of
the measuring devices of the machine which were
existing at the instant that the probe stylus was in a
state of zero deflection and still in contact with the
surface.

This method allows an analogue probe to be used as if
it were a very accurate touch trigger probe since the
value of the machine's outputs is determined at the
point where the stylus contacts the surface, in the
5   same way as a trigger probe. The higher accuracy of
this method derives partly from the fact that many data
points are taken in order to determine the point of
contact, so that errors tend to be averaged out.
Furthermore, a particular advantage is that the contact
10   point determined corresponds to zero deflection of the
stylus, and consequently zero contact force between the
stylus and the object, so that errors due to bending of
the stylus and/or of the machine structure do not
arise.

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Summary of the Invention

A first aspect of the present invention provides a
method of measuring an artefact using a machine on
20   which a measuring probe is mounted for relative
movement with respect to the artefact, said machine
having at least one measuring device for providing an
output indicative of the relative position of the
probe, the probe having a deflectable stylus, and at
25   least one measuring device for measuring deflections of
the stylus to provide one or more probe outputs which
are indicative of the amount of deflection of the
stylus from a rest position, the method being
characterised by the steps of:
30   causing relative movement between the probe and
artefact to bring the stylus into contact with the
surface of an artefact and continuing said movement for
a limited distance after initial contact has been made
between the stylus and the artefact;

recording the outputs of the machine and of the probe at a plurality of instants, during both the periods of contact and non contact between the stylus and the artefact;

5   providing a model of the probe and CMM outputs which models the outputs both during contact and non contact between the stylus and the artefact;

fitting the model to the data and thereby determining the values of the outputs of the measuring

10   device or devices of the machine relating to the contact position at which the stylus contacts the artefact with zero contact force; and

combining said outputs of the measuring device or devices of the machine at said contact position with

15   the probe deflection at the contact instant to establish the contact position at zero force.

The outputs of the measuring devices of the machine and the probe may be recorded during one or both of the

20   probes relative movement towards the artefact and away from the artefact.

Preferably the model is a break line. The break line may comprise a line of zero gradient and at least one

25   sloped line.

Preferably the values of the outputs of the machine when the stylus contacts the artefact with zero contact force are determined by an optimisation procedure.

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A second aspect of the present invention provides a method of measuring an artefact using a machine on which a measuring probe is mounted for relative movement with respect to the artefact, said machine

having at least one measuring device for providing an
output indicative of the relative position of the
probe, the probe having a deflectable stylus and at
least one measuring device for measuring deflections of
5   the stylus to provide two or more probe outputs which
are indicative of the amount of deflection of the
stylus from a rest position along at least two probe
axes, the method including the steps of:

causing relative movement between the probe and
10 artefact to bring the stylus into contact with the
artefact and continuing said movement for a limited
distance after initial contact has been made between
the stylus and the artefact;

recording the outputs of the machine and of the
15 probe at a plurality of instants, in at least part of
the period of contact between the stylus and the
artefact;

from said outputs of the machine and of the probe,
determining the values of the outputs of the machine
20 relating to the contact position when the stylus
contacts the artefact with zero contact force;

wherein the data from each probe output is used
individually to determine a single contact position.

25 A third aspect of the present invention provides a
method of measuring an artefact using a machine on
which a measuring probe is mounted for relative
movement with respect to the artefact, said machine
having at least one measuring device for providing an
30 output indicative of the relative position of the
probe, the probe having a deflectable stylus and at
least one measuring device for measuring deflections of
the stylus to provide one or more probe outputs which
are indicative of the amount of deflection of the

stylus from a rest position, the method including the
steps of:

5 causing relative movement between the probe and
the artefact to bring the stylus into contact with the
artefact and continuing said movement for a limited
distance after initial contact has been made between
the stylus and the artefact;

recording the outputs of the machine and of the
probe at a plurality of instants, in at least part of
10 the period of contact between the stylus and the
artefact, both for relative movement between the probe
and artefact towards and away from one another;

from said outputs of the machine and of the probe,
determining the values of the outputs of the machine
15 relating to the contact position when the stylus
contacts the artefact with zero contact force, both for
relative movement between the probe and artefact
towards and away from one another, thereby determining
two apparent contact positions;

20 and wherein the true contact position is
determined by combining the two apparent contact
positions.

The true contact position is thereby corrected for time
25 delays.

The combination of the two apparent contact positions
may comprise taking an average of the two apparent
contact positions.

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The average may be weighted by the relative speeds of
the machine during the relative movement between the
probe and the artefact in each direction.

A fourth aspect of the invention comprises a method of measuring an artefact using a machine on which a measuring probe is mounted for relative movement with respect to the artefact, said machine having at least

5 one measuring device for providing an output indicative of the relative position of the probe, the probe having at least one measuring device for measuring the distance from a surface of the artefact to provide one or more probe outputs, the method including the steps

10 of:

causing relative movement between the probe and the artefact;

recording the outputs of the machine and of the probe at a plurality of instants, both for relative

15 movement between the probe and artefact towards and away from one another;

from said outputs of the machine and of the probe, determining two apparent surface positions of a surface of the artefact, the two apparent surface positions

20 relating to relative movement between the probe and artefact towards and away from one another respectively;

and wherein the true surface position is determined by combining the two apparent surface

25 positions.

The true contact position is thereby corrected for time delays.

30 The combination of the two apparent surface positions may comprise taking an average of the two apparent surface positions.

The average may be weighted by the relative speeds of

the machine during the relative movement in between the probe and artefact in each direction.

Brief Description of the Drawings

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The invention will now be more particularly described, by way of example only, with reference to the accompanying drawings in which:

Fig 1 is a diagrammatic representation of a CMM
10 with which the invention is used;

Fig 2 is a graph of probe outputs against CMM position for a prior art method;

Fig 3 is a graph of probe output against CMM position for a first embodiment of the present
15 invention;

Figs 4A-4D illustrate the break line interpolation model of the second embodiment of the current invention;

Fig 5 illustrates the break line interpolation
20 model fitted to measurement data;

Fig 6 is a graph of the root mean square error against contact position for each model shown in Fig 5;

Figs 7A-7C are graphs of the individual probe outputs against CMM position;

25 Fig 8 illustrates the break line model being fitted to each probe output individually according to a single contact position;

Fig 9 is a graph of the measured position of the surface along the X axis against the speed of the
30 probe;

Fig 10 illustrates the probe output P against CMM position, both on the way in and the way out at two different speeds;

Fig 11 illustrates the break line model with a

time delay line added; and

Fig 12 illustrates the graph of Fig 12 showing the correction for the time delay.

5   Description of Preferred Embodiments

A known method of using a scanning probe to take touch trigger measurements of a surface will now be described with reference to Figs 1 and 2. Referring to the

10   drawings, Fig 1 shows a coordinate measuring machine (CMM) 2 which is well known in the art. The CMM 2 has a machine table 3 on which an object 5 to be measured is mounted and a spindle 4 which is moveable in X,Y and Z relative to the machine table 3. Transducers (not

15   shown) are provided to measure the relative position of the spindle with respect to the machine table in X,Y and Z. Variations of this set up are known in which relative motion between the object and the probe are provided by other means, for example by moving the

20   object whilst the probe remains stationary.

A probe 6 is mounted on the spindle 4 of the CMM 2. The probe 6 has a deflectable stylus 7 with a workpiece contacting tip 8. Transducers are provided in the

25   probe to measure the deflection of the stylus. An example of such a probe is described in US Patent No. 3,876,799 in which a stylus is supported relative to a fixed structure by three serially connected parallel springs. Displacement of the stylus relative to the

30   fixed structure is transduced by optical means, comprising three optical scales provided on a member to which the stylus is connected and corresponding readheads located on the fixed structure adjacent the optical scales.

The probe is driven by the machine controller towards
the object. During this movement the readings of the
CMM transducers are continuously fed into a computer
which forms part of the overall machine control system.

5

Whilst the stylus is in its rest position (i.e. the
position which it occupies when no external forces act
on the stylus tip), the output of the probe transducers
is set to zero.

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As soon as the stylus tip is deflected by contact with
the object, the output of the probe transducers starts
to change. This causes a signal to be sent to the
machine controller (in known manner) to commence

15   reading the machine scales and to output the values to
the computer. A further limited amount of travel of
the machine is allowed by the computer and then the
machine is stopped and reversed. During the reversing
movement, the outputs of the machine transducers and of

20   the probe transducers are recorded simultaneously at
intervals. The controller stops the machine and the
computer calculates from the readings a notional
straight line through the readings and extrapolates
back to find the reading of each of the machine scales

25   which would have existed at the very instant the stylus
ball contacted the surface. This is the reading of
each of the machine scales at the point when the output
of the probe transducers was last at the level equating
to the rest position of the stylus.

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Fig 2 shows by a graphical representation the
calculations which are made by the machine's computer.
The vertical axis shown represents the outputs of the
probe transducers and the horizontal axis represents

the CMM transducer outputs of one axis. As the machine
continues its limited movement after contact has been
made between the probe stylus and surface, the probe
outputs increases as the stylus is deflected. A
5 straight line 10 is plotted from the probe outputs and
extrapolated back to find the machine scale readings at
the probe output representative of zero. At this point
12, the probe stylus has zero deflection and thus there
is zero force between the stylus and the object.

10

This method has several disadvantages. Firstly, the
probe outputs may have offsets resulting in the
transducers of the probe not reading zero when the
stylus is in its rest position. This has the result
15 that the extrapolation calculation finds the position
of the CMM at the measured zero deflection rather than
the position of the CMM at the contact point.

A second disadvantage is the uncertainty associated
20 with the use of extrapolation. When a line is fitted,
the uncertainty of an extrapolated point, which is
outside the area of the measured points, is larger than
the uncertainty of a point in the middle of the
measured data.

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A first embodiment of the present invention will now be
described with reference to Fig 3. As described above,
the probe is driven by the machine controller towards
the object and during this movement the readings of the
30 CMM transducers are constantly fed into the computer.
As before, once the stylus tip is deflected by contact
with the object, the probe travels a further limited
distance and then is stopped and reversed. During
movement in either the forward, reverse or both

directions, the outputs of the machine transducers and
of the probe transducers are recorded simultaneously
and stored. However, in this embodiment the probe
outputs are also recorded whilst the probe is free
5 (i.e. not in contact with the surface of the object).
Whilst the probe is free, the probe outputs are
constant (except for noise). However, due to offsets,
the probe outputs when the probe is free may not be
zero. In Fig 3, line 16 illustrates the probe outputs
10 when the probe is free. When the stylus is in contact
with the surface of the object, the probe outputs
change with CMM position as the stylus is deflected.
Line 18 is a best fit line through these points.

15 The point 22 at which these two lines 16 and 18
intersect is the point at which the stylus tip of the
probe first contacts the surface.

This method has the advantage that it allows for the
20 probe offsets when the probe is free, unlike the prior
art method in which the probe data is extrapolated back
to zero deflection.

In a second embodiment of the present invention, the
25 probe output data and CMM transducer data is fitted to
a model which describes the reality more closely, as
described in more detail below.

As before, the probe is driven by the machine
30 controller towards the object and once the stylus tip
is deflected by contact with the object, the probe
travels a further limited distance and then is stopped
and reversed. Both the CMM transducer outputs and the
probe outputs are recorded continuously (i.e. whilst

the probe is free and in contact with the object) and
on both the forward or reverse movement.

As shown in Fig 4A, the model comprises a break line 34
5   which is determined by a linear combination of two or
more functions, a constant that fits the free value of
the probe (shown in Fig 4B) and at least one sloped
line that allow the model to fit any corner. Each of
the functions is multiplied by a parameter α, β and γ
10   respectively. The sloped line shown in Fig 4C fits the
probe contact data in the forward direction and the
sloped line shown in Fig 4D fits the probe contact data
in the reverse direction.

15   The sloped lines for the forwards and reverse
directions shown in Figs 4C and 4D may have different
gradients. This produces a better fit for the probe
behaviour whilst it is in contact with the object.

20   The model must be fitted to the data and the contact
point must be found. The model may be fitted to either
one or both of the data collected in the forward and
reverse directions (herein after referred to as the in-
way and out-way data respectively). In a first step a
25   possible contact point is chosen. The model is fitted
to the data using the linear least squares method. The
root mean square error of the fit (between the data and
model) is then determined. This process is then
repeated using a new possible contact point.
30

Fig 5 illustrates a graph of probe output against CMM
position. Lines 36, 38 and 40 illustrate the model
fitted to the data 34 three times, each with a
different chosen contact point.

Fig 6 illustrates a graph plotting the contact point
position against the root mean square error between the
measurement data and the corresponding model. A curve
42 is formed and the minimum of the curve (i.e. the
5   minimum root mean square error) is the best possible
fit between the data and model and therefore indicates
the contact point position.

The minimum search can be done using a simple dichotomy
10   method or a Newton method.

An advantage of using the break line model is that
extrapolation of the measurement data to find the
contact point is not required. Instead, the contact
15   point is in the middle of the model.

As data is taken before and after the contact position,
the present method performs an interpolation at the
contact position instead of an extrapolation to probe
20   output equals zero or free space value.

This method also has the advantage that as the probe
deflection is determined at the contact point, both CMM
position and stylus tip position are known at the
25   contact instant. This differs from the extrapolated
method described above in which the probe deflection is
not known at the contact point, rather the position of
the CMM is known when the probe deflection should be
zero. This enables return to zero and hysteresis
30   errors of the probe to be determined.

The deflection of the stylus of the probe is measured
by probe transducers. Typically there may be three
probe transducers measuring deflection of the stylus in

three orthogonal directions. The outputs of these
transducers are denoted P, Q and R. The individual
probe outputs P, Q and R may be computed and converted
into a single dimension value F(P,Q,R) which shows

5 variation of the probe outputs in any direction, as
illustrated in Fig 7a. For example, the single
dimension value $F(P,Q,R) = |P|+|Q|+|R|$.

As previously described in the extrapolation method,

10 the probe outputs are constant before the contact
position and increase after the contact position. The
gradient of the change in probe outputs against CMM
position is determined by the direction in which the
probe contacts the surface and the output gains after

15 the contact position. By using the sum of the absolute
values of each of the probe outputs, the direction in
which the probe contacts the surface no longer effects
this gradient. The contact point may be extrapolated
from the probe output function F(P,Q,R) against CMM

20 position.

However this is not a perfect solution. If the probe
is not zeroed before extrapolating, the individual
probe outputs may not equal zero before contact because

25 of errors such as drift and return to zero which modify
the probe offsets. As the probe output function
F(P,Q,R) is extrapolated to probe output = 0, the zero
point is the intersection between the slope of the
probe output function F(P,Q,R) and the CMM position

30 axis. However, the different offsets of the individual
probe outputs can cause the zero point of the probe
output function F(P,Q,R) to be calculated in the wrong
position.

Furthermore, in a few directions of probing the sum of
the individual probe outputs is zero. This can cause
the sum of their absolute values F(P,Q,R) to give an
erroneous contact point position.

5

Fig 7b illustrates a situation where the sum of the
probe outputs is zero, which causes the sum of the
absolute values F(P,Q,R) to give the wrong contact
point. Fig 7c illustrates a case where the probe is
10   not zeroed before extrapolating and the wrong offsets
of the probe outputs causes the calculated contact
point to be incorrect.

These considerations effect other calculations
15   involving P,Q and R, such as $\sqrt{P^2+Q^2+R^2}$.

These problems are overcome in the present invention by
analysing each output separately. By using the data
from each probe output P, Q and R, different probe
20   offsets do not effect the final contact position. As
illustrated in Fig 8, the break line interpolation
model is fitted to measurement data from each output
P,Q and R individually to determine a single contact
position. Thus if probe outputs P,Q and R differ, this
25   does not give an error in the contact position. If
there are differences in the contact positions
determined using each probe output, the best contact
position may be determined using an optimisation
procedure.

30

In the same manner, the separate probe outputs may be
used individually to determine a single contact
position in the extrapolation method of the prior art,
as illustrated in Fig 2.

The probe outputs may be effected by several types of
errors, such as return to zero.

5   The probe may have a return to zero error. When a
scanning probe takes a point measurement, the free
position of the stylus before and after the probing are
not necessarily the same. Part of the difference of the
stylus position before and after probing is measured by
10   the probe transducers and this is the return to zero
error. The return to zero error may be due to the
effect of probe dampers for example.

These errors can be observed in a repeatability test in
15   which a surface is repeatably probed, with measurement
data being collected both on the probe's forward and
reverse movement from the surface. This surface is
probed at the same position and along the same
direction each time. This repeatability test allows the
20   unidirectional repeatability of the probe to be tested.

Because of return to zero the position of the zero
force contact point will change during the
repeatability test as the history of probing influences
25   these variations.

If data are taken during both in and out moves, the
averaging of variations caused by errors such as return
to zero reduce their effect and also enable the return
30   to zero to be measured.

The difference in CMM position between the first in and
the first out data is a measurement of the return to
zero.

Therefore the return to zero of a probe can be determined from the first in and first out data of the CMM.

5 Components of the probe such as the electronics, filters, probe dampers and the stylus time response can cause a time delay between the stylus contacting the surface and the corresponding probe outputs. The present method of interpolating the break line model

10 allows these errors due to time delays to be corrected.

The time delay may be observed by probing a surface in the same direction several times at different speeds. Probe data is collected both on the way in and the way

15 out. Fig 9 is a graph of the measured position of the surface along the X axis against the speed of the probe. Line 70 illustrates the measurements taken using the extrapolate to zero method of the prior art. It can be seen that as the speed of the probe movement

20 increases, the measurement error increases.

Lines 72 and 74 illustrate the measurements taken using the break line interpolation model of the present invention taken on the way in and way out respectively.

25 It can be seen that the measurements of lines 72 and 74 corresponding to the in and out measurements taken using the break line interpolation model have linear errors. As both the in and out errors are symmetrical, it appears that these errors are due to the time delay,

30 the value of which can be determined from the gradients of the lines 72 and 74. The time delay occurs between the way in and way out measurements, and it is possible to identify the delay if measurements are taken both on the way in and the way out.

Fig 10 illustrates the probe output P against CMM
X-axis position both on the way in and on the way out
at two different speeds. Probe output P on the way in
and probe output P on the way out at a faster speed are
5   shown by lines 90,92 respectively, whilst probe output
P on the way in and probe output P on the way out at a
slower speed are shown by dashed lines 94, 96
respectively. A time delay effect 80 can be observed
between the way in and the way out measurements 90,92
10   at the faster speed. As the probe is moved at constant
speed, a constant delay is observed.

A second time delay effect 82 can be observed between
the way in and way out measurements 94,96 at the slower
15   speed. The time delay can therefore be seen to
increase as the probe speed increases.

The break line interpolation model can correct for the
data acquisition delay described above. Use of the
20   first contact point on the way out has the advantage
that it allows single point measurement on the object
without form error. However, the time delay must be
corrected in order to obtain the correct contact
position.
25

As discussed above, the time delay appears between the
way in and way out data. Therefore it is possible to
determine the value of the time delay if data is
collected in both directions.
30

Fig 11 shows the break line model with a time delay
line added. The two sloped lines are the way in 90 and
way out 94 measurement data taken whilst the stylus is
in contact with the surface. The CMM contact point

calculated using the way out measurement data is
represented by T. The time delay between in and out
lines is shown as dT. Where the in-way and out-way
speeds are the same, the way out contact position
5   corrected for time delay errors is T+dT/2. However
where the in-way and out-way speeds are not the same,
the term dT/2 is replaced by a weighted average of the
in-way and out-way speeds.

10   This delay identification optimises two variables T and
dT using Newton multivariate minimisation method.

Line 75 on Fig 12 illustrates the performance of this
break line interpolation with delay compensation.
15
The contact interpolated point with delay
identification has no slope error against speed of CMM,
meaning that the time delay is corrected by this
identification method.
20
This method of delay correction is also suitable for
use with the extrapolation method shown in Fig 2.

This method of correction for time delay is also
25   suitable for use with a non-contact probe, for example
an optical probe, in which time delays may be caused
by, for example, processing delays. In this case, the
apparent surface position of the object is measured
both as the non-contact probes moves towards and away
30   from the object. As above, the corrected surface
position is determined by taking an average of the two
apparent surface positions, the average being weighted
by the speed of the machine in each direction.

It is also possible to collect the data in both
directions and fit the break line model to this data to
determine a single contact position. This has the
effect of averaging the differences in the data
5   collected in both directions. Likewise the data
collected in both directions may be extrapolated to
find a single contact position, using the method of the
prior art.